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The Inspection of Wire Ropes in Service: A Critical Review

by Herbert R. Weischedel*

Abstract

The art of wire rope inspection has progressed rapidly during the past few years. Electromagnetic instruments now available can reliably test wire ropes in service and can remedy the shortcomings of visual wire rope inspection methods. This paper critically reviews present wire rope inspection procedures and modern test instrumentation.

Introduction

A recent statistical analysis[1] of over 8000 laboratory and field test records revealed some interesting facts on the condition of wire ropes in service.

- Approximately 10 percent of all ropes considered showed a strength loss of over 15 percent; more than 2 percent of the ropes had lost over 30 percent of their nominal strength. In other words, while still in service, 10 percent of all ropes were in an unacceptable and potentially hazardous condition, and 2 percent of the ropes were in an extremely dangerous condition.
- Conversely, more than 70 percent of all ropes in the sample were removed from service with little or no strength loss.
- The above findings suggest that only a very small percentage of all ropes was replaced in a timely fashion.

These observations vividly illustrate the unreliability of the prevalent wire rope inspection methods, especially of visual wire rope inspections: Although the majority of all ropes are retired prematurely, as a precaution, many ropes in service are severely degraded and in a dangerous condition. Because visual inspections are unreliable, many users replace wire rope at fixed intervals, usually based on some ton-mileage figure.

Present visual inspection methods have serious deficiencies. They do not guarantee wire rope safety, because they simply cannot reliably identify unsafe wire ropes which should be replaced. Also, they are wasteful, because they usually cannot identify wire ropes that have additional service life left.

Because failure of wire ropes inevitably causes a serious hazard, safety codes and authorities mandate periodic inspections. As an example, that part of the US Code of Federal Regulations (30 CFR 811) dealing with wire rope safety in the mining industry is reproduced in Appendix A. These regulations concisely summarize present wire rope inspection methods and the major causes of wire rope failure.

Similar regulations apply to all other areas of wire rope usage. The Safety Code for Elevators (ANSI A17.1) including the Elevator Inspectors Manual (ANSI A17.2) and the Safety Code for Overhead and Gantry Cranes (ANSI B30.2.0) provide but a few additional examples of safety codes dealing with wire rope safety.

All safety codes give specific criteria for the replacement of wire rope. Obviously, test procedures should be able to determine whether or not these replacement criteria apply. All inspection procedures, especially the predominant visual inspection method, are deficient in this respect.

A word about government certification of nondestructive test instruments: Only the Canadian government requires approval of rope inspection equipment. Neither the US government nor any other government, worldwide, requires or grants instrument certification.

Deterioration of Wire Rope

The principal deterioration modes of wire rope can be categorized as follows.

Loss of Metallic Cross-Sectional Area (LMA)

External abrasion is caused by rubbing along floors or other surfaces. Internal abrasion is caused by nicking, high pressures, or poor lubrication. Corrosion (external and internal) is caused by environmental conditions or poor lubrication.

Localized Faults (LF)

Broken wires are caused by fatigue, plastic wear, martensitic embrittlement, or mechanical damage. Kinks and other mechanical damage may also occur.

Although many nondestructive test procedures, employing radiation and optical, acoustical, and mechanical methods, have been proposed and tried in the past, at the present time, only visual and electromagnetic test methods are practical.

Visual Inspection

The most obvious and the simplest, but not the easiest, method of testing a rope for flaws is by visual inspection. The two basic types of visual inspection procedures are (1) the "rag-and-visual" method and (2) rope diameter measurements. Both procedures are discussed here.

The rag-and-visual method is useful for the detection of broken wires. This

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obvious method always supplements any other test procedure. Traditionally, a wire rope is inspected for broken wires in the following manner: The inspector is stationed next to the rope and grasps it with a rag or gloves. Broken wires will often porcupine and, as the rope moves at inspection speed, catch the rag or glove. The rope is then stopped at that point, and the inspector tries to ascertain the rope condition by a visual examination. This procedure is satisfactory for nonpreformed rope, where broken wires porcupine.

Since most wire rope is preformed, a different and more tedious test procedure must usually be applied: The rope is moved two or three feet at a time and visually examined at each stop. For a thorough inspection, strong lights, mirrors, a magnifying glass, and rope cleaning compound are frequently used in addition to rags. Because of the limited attention span of the examiner, and because the rope is often covered with grease, the reliability of this cumbersome and time-consuming method leaves a great deal to be desired.

The visual-and-rag method, time-consuming and unreliable as it is, is adequate for the detection of broken surface wires in cases where life is not imperiled by failure to detect a few broken wires and where distributed defects, such as internal and/or external abrasion and corrosion, are not a problem. An elevator cab, for example, is supported by four to eight wire ropes, each with a considerable margin of safety. Furthermore, most elevators operate in a well protected environment, where corrosion is not a problem. Because the rag-and-visual method usually cannot detect internal flaws, elevator ropes have fiber cores to prevent internal rope damage. Therefore, visual rope inspection for elevators which operate in a well protected environment can be considered adequate.

On the other hand, visual inspection methods, even for elevators, are unnecessarily time-consuming and, therefore, expensive. Since some wire ropes are not easily accessible, the examiner has to operate in strenuous and awkward positions, sometimes for long periods of time. Furthermore, because the inspector is in close proximity and in direct contact with the moving wire rope, the visual-and-rag method is potentially hazardous. Several serious accidents during rag-and-visual inspections have occurred in the past.

Another visual inspection method is the measurement of the rope diameter with a caliper. This procedure is useful for the detection of loss of metallic cross-sectional area. Evaluations of rope diameter measurements are based on a comparison of the original diameter—when new and subjected to a known load—with the current reading under like circumstances. A marked reduction of rope diameter indicates degradation. A change of rope diameter can indicate external and internal rope damages, such as excessive external abrasion, internal and external corrosion, loosening or tightening of rope lay, and broken cores. Unfortunately, these sorts of damage often do not cause a change in rope diameter, making this method, at best, questionable.

Rope diameter measurements are often unreliable, cumbersome, and not easy to evaluate. Most standards, for example, require that rope is to be removed if the outer wire wear exceeds one-third of the original diameter of the outer wires. Wire wear is not easy to determine by visual methods, so discovery relies upon the experience of the inspector. Another example, internal corrosion, is a very serious type of rope degradation and most often occurs with no external evidence detectable by the visual-and-rag method and/or diameter measurements.

In mining, aerial tramway, and chairlift applications, rope failure usually has serious and fatal consequences. Inspection solely by visual methods for these ropes must be considered inadequate and can be justified only if no other alternatives are available. As a consequence of the unreliability of the presently predominant visual inspection methods, wire rope is often replaced prematurely in an attempt to maintain a sufficient safety margin.

Summary: Visual Rope Inspection

Visual rope inspection can be characterized as follows.

Advantages

Visual rope inspection is very simple and does not require expensive instrumentation. It is adequately reliable for noncritical applications with high safety margins and where internal rope degradation is not a problem. Despite its many deficiencies, it is an important inspection method which should supplement any other test procedure.

Disadvantages

Because of their inherent difficulty and unreliability, visual rope inspections require a trained and experienced inspector.

Only surface flaws can be detected. The inspector cannot detect internal flaws such as internal corrosion or abrasion. If the rope is covered with lubricating grease or plastic sealing materials, inspection is impossible.

Inspections are not sufficiently reliable for life-sustaining applications with low safety margins. Reliability depends on the attention span, the judgment, and the experience of the inspector.

If only visual inspection methods are used, premature rope retirement is often necessary, but not sufficient, to maintain an adequate safety margin.

Inspection is time-consuming, cumbersome, expensive, and potentially dangerous for the examiner.

An objective record of the rope inspection is not available.

Electromagnetic Inspection

Electromagnetic methods for nondestructive testing of wire ropes are more reliable than purely visual methods. Although they should not completely replace careful visual inspections, nondestructive inspections provide great insight into the condition of a rope. Because of its reliability, especially if supplemented by visual inspections, nondestructive testing has gradually become an accepted method for the inspection of wire ropes in the mining industry, for ski lifts, and for other applications in North America, Europe, and South Africa.

Two different and distinct types of nondestructive inspection methods have evolved: (1) localized fault inspection (LF inspection) and (2) inspection for loss of metallic cross-sectional area (LMA inspection).

Similar to the rag-and-visual method, LF inspection is suited only for the qualitative detection of localized flaws such as broken wires or corrosion pitting. Therefore, small hand-held LF instruments have been called "electronic rags."[2,3]

The LMA inspection method is suited for the detection and quantitative evaluation of distributed flaws such as abrasion and corrosion. Much more reliable and convenient than visual diameter checks, LMA inspection can replace diameter measurements made with a caliper. Therefore, LMA instruments could be called "electronic calipers." The more advanced of the presently available instruments allow a simultaneous LMA and LF inspection.

All of the present rope inspection instruments are hinged and can be easily mounted on the rope in the field. Except in the most extreme conditions, inspection of any installed rope is possible. One of the available instruments can even inspect tightly spaced elevator ropes. Some instruments are operated by rechargeable batteries, which makes their operation very convenient even under adverse field conditions.

To perform an inspection, the inspector places the instrument on the rope. While the rope travels through the instrument, a strip-chart recorder and/or a cassette tape recorder records the test signals. Using audiovisual signals such as buzzers, headphones, or indicator lights, the inspector, assisted by the test instrument, can also inspect the rope visually. He can then compare visible flaws with the recorded chart patterns. Most instruments come with an electromechanical distance counter, which makes it easy to correlate the actual flaw position on the rope with the chart recording.

A program of regularly scheduled nondestructive inspections, typically at four- to six-month intervals, is of particular value for safe and extended rope usage. Periodic inspections allow a more accurate assessment of the rope condition than a mere single inspection. To establish baseline data for the subsequent inspections, this program should be initiated by an electromagnetic inspection of the new rope after its installation and after a sufficient break-in period. Since an accurate and objective record of the rope condition is available for each inspection, it is possible to compare rope data at the time of each inspection. A complete documentation of a rope's gradual deterioration, throughout its entire service life, is therefore available. The end of safe service life is usually reached when the rope degradation exceeds certain limits and/or when the degradation rapidly accelerates between inspections. Furthermore, periodic inspections can prevent premature rope deterioration by making the operator aware of faulty operating conditions such as worn or misaligned sheaves.

While the operation of most instruments requires considerable skill, some instruments are easy to operate even for moderately skilled personnel. Chart recordings are simple to interpret, and this can be done on site. For comprehensive evaluation, a cassette tape recording can be produced which is returned to the lab, where a thorough computer-aided analysis is performed. Successive inspection results are compared with data from previous inspections.

Inspections by electromagnetic methods are safer, faster, more convenient, and in many cases less expensive than visual inspections. Since the instrument can be attached to the rope, the inspector does not need to be in physical contact with the rope, making inspections safer and more convenient. Time savings of approximately 80 percent as compared to visual inspections, with associated savings in man-hours, have been reported.[3]

Summary: Electromagnetic Rope Inspection

In summary, electromagnetic wire rope inspection can be characterized as follows.

Advantages

Under all conditions, it is much more reliable than purely visual inspection.

A permanent and objective record of the rope condition is readily available.

External and internal defects can be detected.

Since nondestructive rope inspections are very reliable, rope life can usually be safely extended. Premature rope replacement can be avoided while wire rope safety is improved.

Electromagnetic inspection is much more convenient, less time consuming, and less dangerous for the inspector than purely visual methods.

Disadvantage

Suitable instrumentation and a trained operator are required.

Presently available wire rope inspection instruments are discussed, categorized, and critically compared in the following.

Electromagnetic Wire Rope Inspection: Performance Criteria

To compare the performance of different instruments, we first define and discuss the following performance criteria. These criteria can serve as an objective and quantitative performance measure and can make the comparison of available wire rope inspection instruments more concise and rational.

Resolution

The *resolution* of a transducer is measured as the smallest distance between flaws for which the transducer provides distinctly separate flaw indications. *Resolving power* is defined as the reciprocal of resolution.

Quantitative Resolution

The *quantitative resolution* is the required minimum length of a uniform flaw for which the sensor provides an accurate quantitative measurement of a rope's CMA within a predefined small error limit. *Quantitative resolving power* is defined as the reciprocal of the quantitative resolution.

Because all sensors have finite quantitative resolving power, minimum flaw lengths are always required for an accurate quantitative fault identification. The concept of "quantitative resolution" is important for specifying and comparing the performance of LMA instruments.

The following example illustrates the importance of a high quantitative resolving power. Consider a (hypothetical) rope with a 10 percent, uniform LMA extending over a length of 2 in. (5 cm). An instrument with a quantitative resolution of 2 in. (5 cm) can determine the exact LMA caused by this flaw. However, an instrument with a quantitative resolution of 20 in. (51 cm) would indicate the same fault as a 1 percent LMA extending over a length of 20 in. (51 cm)—a very inaccurate indication of the true rope condition. Of course, both instruments would give a correct indication of uniform faults extending over a length of 20 in. (51 cm) or longer.

An analogy can illustrate the problem: The strength of a chain is determined by the strength of its weakest link and not by the average strength of some of its links. Analogously, the strength of a rope is determined by the minimum instantaneous cross-sectional area along the rope's length, and not by some average value of the rope's cross-sectional area.

High quantitative resolving power is important. This importance becomes evident when considering typical rope failures caused by LMA. For instance, in many applications, high humidity causes accumulation of water inside the rope and causes corrosion. Therefore, most of these ropes, when close to retirement, show advanced internal corrosion, often combined with internal interstrand wear. Usually, this deterioration is not visible from the outside.

Corrosion causes typical patterns of metal loss: corrosion pitting and corrosion patches. Pitting occurs in the form of very short localized losses on the surface of individual wires, while corrosion patches extend over a number of wires. Corrosion patches have a tendency to form groups with the length of individual patches in the group extending over only a few inches (ca. 7–11 cm). Often, some of the wires within a patch are completely separated by corrosion and form clusters of broken wires. To determine a rope's metal loss and loss of strength with reasonable accuracy, high quantitative resolution, of no more than a few inches, of the test instrument is obviously important.

Penetration

The penetration of a transducer is measured by the ratio of the signal amplitude, caused by an internal flaw, to signal amplitude, caused by an identical surface flaw. This ratio is also called the Penetration Ratio. Note that the penetration ratio depends on the defect geometry.

The amplitude of flaw related pulses depends on the location of the flaw within the rope cross section (its eccentricity). The closer the flaw is to the sensor, the higher is the corresponding flaw signal amplitude.

Ideally, a sensor should have a penetration ratio of one. This means that identical internal and external flaws should be indicated by equal signal amplitudes. Actual sensors always have penetration ratios less than one, which depend on the geometry of the defect.

Signal-to-Noise Ratio

Only test signal components which are caused by rope defects are of interest. That part of the test signal which is not caused by defects is considered noise. The signal-to-noise ratio is defined as the amplitude ratio of the defect related signal component to noise.

A steel wire rope is an arrangement of

separate wires wound in a helical shape to form strands, which are then laid together in a helix to form the rope. This very intricate and nonhomogeneous arrangement of wires forms many cavities between the wires and strands, which mimic rope flaws and cause associated signals. These structure-related signals will be referred to as *intrinsic noise.* Intrinsic noise causes serious problems, and it always makes test signals very noisy.

The inhomogeneous rope surface, which is very close to the sense coils, is a primary cause of the intrinsic noise signal. Since the penetration ratio is always less than one, the signal-to-noise ratio, especially for internal flaws, can become quite small. The intrinsic noise is superimposed on defect signals and can significantly distort and conceal them.

The signal-to-noise ratio of a sensor is not uniquely defined. It is a very complicated function of sensor parameters, rope structure, and defect geometry. For a convenient comparison of signal-to-noise ratios, different instruments should be used to inspect the same rope under identical test conditions. Signal-to-noise ratios can then be determined and compared by evaluating and comparing the test signals.

Flaw Detectability

Flaw detectability is defined as the smallest cross-sectional area change which the sensor can detect. Note that flaw detectability is strictly a function of and intimately related to the signal-to-noise ratio. A signal-to-noise ratio greater than one is required for flaw detection.

Sensitivity

The sensitivity of a sensor is defined as the signal amplitude caused by a predetermined flaw. In designing rope test instruments, sensitivity usually causes no problems, as it can easily be increased by increasing the gain of the signal amplifiers.

"Sensitivity" specifications are arbitrary and meaningless. Note that flaw detectability is a function of signal-to-noise ratio rather than sensitivity.

Repeatability

Many sensors used for rope inspection are either subdivided or otherwise not rotationally symmetric. Hence, noise as well as flaw signals depends on the angular position of the rope with respect to the sensor head, and complete repeatability of signals cannot be assured for some instruments.

Magnetic Interference

Since insulating materials for magnetic fields do not exist, magnetic flux is difficult to contain. All electromagnetic rope test instruments are surrounded by a magnetic leakage field. Therefore, foreign ferrous objects, such as steel beams, pipes, steel floors, or tightly spaced ropes, in the immediate vicinity of the test instrument can influence the test results. Preventing lateral movement of foreign steel objects—for instance, of adjacent ropes—relative to the sense head eliminates or minimizes problems caused by interference.

Weight and Size

Because instruments are used in the field for on-site inspections, sensor heads have to be mounted on the rope. Consequently, the size and weight of instruments are important. The weight of the permanent magnet assembly determines the weight of the sensor head.

For optimum performance, the magnetizer has to drive the rope into magnetic saturation under all operating conditions. To reduce the weight of the sensor head without sacrificing performance, advanced instruments use ultrapowerful rare-earth permanent magnets. Other instruments use less expensive and much less powerful permanent magnets made from sintered ferrite material. There is, however, a significant weight and performance trade-off for using these less expensive and less efficient ferrite magnets.

Operating Convenience

For on-site field inspections, the operating convenience of an instrument is very important. Since electric power is not always easily accessible, advanced instruments are battery operated. Most instruments come equipped with a rope footage counter, and other accessories include optical and acoustical flaw indicators, digital flaw counters, stripchart recorders, and cassette tape recorders.

Some other performance criteria sometimes cannot be easily pinpointed and formulated. One such criterion is that the instrument should not exhibit poor performance characteristics.

Electromagnetic Wire Rope Inspection: Prior State of the Art

LF (DC) Instruments

The first practical LF instruments for the inspection of wire ropes were developed in approximately 1935. These instruments were also called "direct current" (DC) instruments because they use DC magnetization of the rope, or "flux leakage" instruments because they measure the magnetic flux leakage surrounding the rope. The technique used in flux leakage testing, shown in Figure 1, is to saturate magnetically a section of the steel rope in the longitudinal direction by strong permanent or electric magnets. Any discontinuity in the rope—such as a broken wire, a broken core, corrosion, or abrasion—distorts the magnetic flux and causes it to leak from the rope. Sense coils or Hall generators, close to the rope, sense the flux leakage. The movement of the rope causes the flux leakage to change and to induce voltages in the sensors. The sensor voltages are suitably combined and processed to produce the test signals.

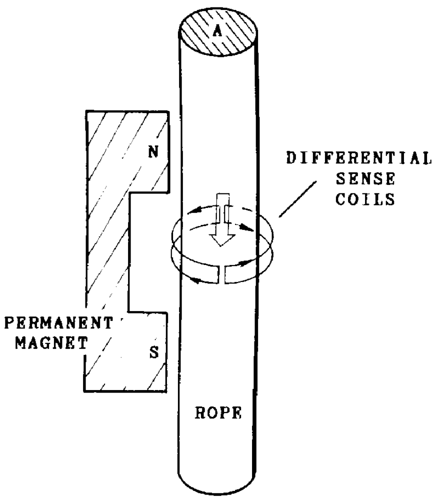

Figure 1—Leakage flux method with differential coils.

Note that the sensors used for LF testing are of the differential type. This means that they can sense only changes of the magnetic flux, not the actual flux itself. Therefore, flaw detectability depends on a rapid change of the magnetic flux in the rope, which is typically caused only by broken wires or corrosion pitting. Differential sensors cannot detect and measure external and internal corrosion and abrasion, which cause a more gradual change of the magnetic flux. Hence, LF instruments are not well suited for the detection and quantitative evaluation of gradual rope deterioration caused by abrasion and corrosion. LF instruments give only a qualitative indication of rope flaws. A quantitative determination of strength loss caused by rope deterioration is not possible. An analogy can elucidate the problem: The height of a mountain cannot be determined with an instrument that can measure only its slope.

Quantitative signal interpretation for LF instruments is difficult, if not impossible. Therefore, an expert is required for signal interpretation. Since corrosion and abrasion are major causes of rope failure, instruments that can detect only localized faults must now be considered obsolete.

Nevertheless, LF inspection can detect many flaws that visual inspections cannot detect. Therefore, LF testing combined with visual inspections is superior to any purely visual method.

Most of the present nondestructive wire rope inspection instruments on the market are of the LF type, especially in Europe and in Canada.[2–18] In the USA, LF instruments are no longer being manufactured. LF instruments were replaced by more advanced instruments which can detect broken wires and simultaneously determine the LMA.

LMA AC Instruments

LMA instruments were first developed as early as 1907. These instruments were also called "alternating current" (AC) instruments because they use AC magnetization of the rope, as shown in Figure 2. The principles used are somewhat similar to the well-known eddy current nondestructive test method. The basic principles were implemented in a variety of ways.[17,19-21] In these instruments, the wire rope serves as the ferrous core of a coil or a transformer. A changing rope cross section changes the impedance or mutual impedance of the test arrangement, and this change serves as a measure of the rope cross-sectional area.

AC testing has been practiced in North America for many years. It suffers from deficiencies such as complicated operation, insufficient quantitative resolution, bad signal-to-noise ratio, and therefore unreliability. A recent study[1] demonstrated the relative ineffectiveness of this method. However, as AC testing gives at least some indication of actual rope deterioration, it is not completely useless. Because of their unreliability, AC instruments will undoubtedly be replaced by other, more accurate instrumentation in the near future.

Because the first practical LMA instruments were of the AC type, all LMA instruments are sometimes referred to as "AC" instruments by the uninitiated. "AC" is occasionally misunderstood to mean "area channel" or "area change." This terminology adds to confusion and is a misnomer. Modern LMA instruments use DC magnetization of the rope and are obviously not AC instruments.

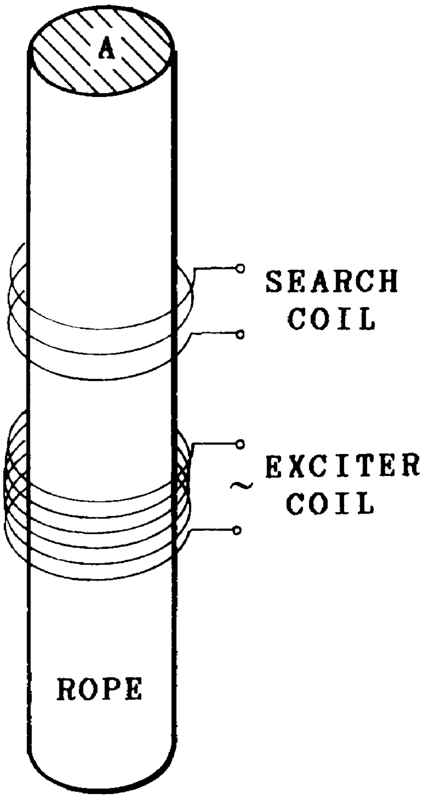

Figure 2—AC main flux method.

Electromagnetic Wire Rope Inspection: Present State of the Art

LMA/LF Return Flux Instruments

LMA instruments of the DC type are more accurate and reliable than AC instruments. These instruments use DC magnetization of the rope, usually by permanent magnets. When the rope is magnetically saturated, the longitudinal magnetic flux in the rope is proportional to the rope's metallic cross-sectional area. Therefore, any LMA can be determined by measuring the longitudinal magnetic flux in the rope.

The first LMA rope testers of the DC type, the Canadian Magnograph[22-24] and the British Plessey[25] instruments, developed in the late 1970s, use Hall generators to measure the magnetic flux. These pioneering instruments made a major contribution to the art of wire rope inspection. The Plessey instrument subsequently encountered patent infringement problems and is no longer commercially available. The Magnograph has overcome its early problems associated with temperature drift of the Hall generators, and its published test results now show it to be a reliable and rugged instrument.[23,24]

The Canadian Rotescograph,[26] developed in the 1980s, emulates the Magnograph principles—with flux gate sensors substituted for the Hall generators to avoid patent infringement and with rare-earth permanent magnets replaced by less powerful ferrite magnets.

These instruments have one inherent shortcoming: To measure magnetic flux density, Hall generators and flux gate sensors have to be physically inserted directly into the magnetic flux path; in other words, the flux to be measured has to intersect the sensors. Obviously, this is impossible when measuring the flux inside a rope. Therefore, these instruments must resort to an indirect method of estimating the magnetic flux inside the rope: They measure some flux density outside the rope and derive an estimate of the longitudinal rope flux from this external flux density measurement.

Figure 3 illustrates the principles used. As in the LF method, strong permanent magnets induce a longitudinal magnetic flux in the rope. Hall generators or flux gate sensors are positioned between the permanent magnets and the rope or, alternatively, in the return flux path of the magnetic circuit to measure the magnetic flux which returns from the rope through the air gap and the permanent magnet yoke. The returning flux is a function of the metallic volume of the rope section positioned between the poles. The flux density in the air gap or in the yoke is therefore an approximate measure of the average metallic cross-sectional area of the rope section between the poles.

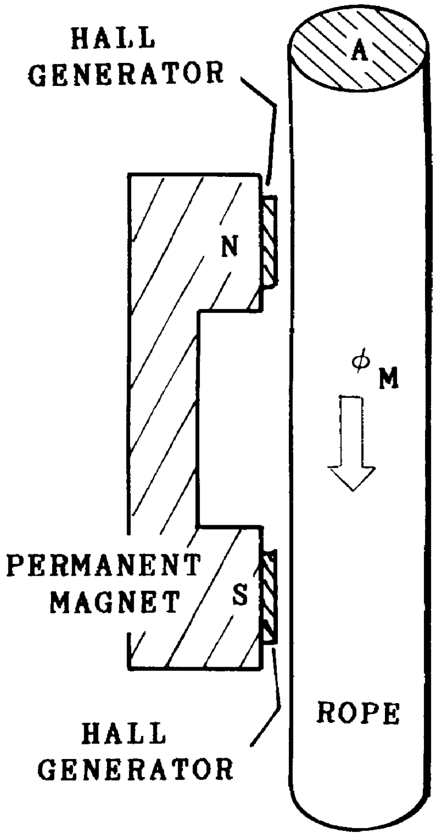

Figure 3—DC return flux method with Hall generators in air gap.

Since these instruments measure the magnetic flux which returns from the rope through the air gap and the permanent magnet yoke, they could be called *LMA return flux* instruments.

In addition to the LMA sensor, an LF sensor is usually also incorporated in these instruments. Although these combined *LMA/LF return flux* instruments represent a considerable improvement over the above mentioned AC and DC test instruments, they still suffer from a rather low quantitative resolving power. By considering Figure 3, one can see that the resolving power depends on the distance of the magnetic poles. These instruments measure only an average value of a rope's metallic cross section between the poles: Any loss of cross-sectional area has to be uniform and longer than the distance between the magnetic poles to be indicated to its full magnitude.

For presently available *return flux* instruments, the pole distance is approximately 20 in. (51 cm) or more. Correspondingly, the loss of cross-sectional area has to be uniform and longer than approximately 20 in. (51 cm) to be indicated to its full extent. These instruments cannot detect and quantitatively evaluate geometrically small or even medium-sized flaws such as localized corrosion, abrasion, or clusters of broken wires. Since most corrosion and abrasion occurs in localized patches, the actual estimate of remaining rope strength is still unreliable.

The resolution of the LMA sensor in return flux instruments is not as good as the resolution of their LF sensor. Remarkably, therefore, quantitative estimates of remaining rope strength rely to a considerable extent on the qualitative LF signal rather than the supposedly quantitative LMA signal.[24] Quantitative signal interpretation, to estimate the actual loss of rope strength, for return flux instruments is complicated, if not impossible. Tests are quantitatively evaluated by proprietary procedures, which are not in the public domain and cannot be critically scrutinized. Their reliability must, therefore, be considered with skepticism.

LMA/LF Main Flux Instruments

A new line of LMA/LF test instrumentation was recently developed in the USA.[27] This new class of instruments allows a direct measurement of the longitudinal magnetic main flux inside the rope, which is not possible with the return flux method. Therefore, in contradistinction to the above-mentioned LMA return flux method, the present approach can be called the "LMA *main* flux" method. The LMA main flux method offers maximum possible resolving power.

Main flux instruments use sense coils to measure the longitudinal magnetic flux inside the rope. As compared to Hall generators and flux gate sensors, which must be physically inserted into the magnetic flux path, sense coils have an inherent advantage: They only have to encircle the magnetic flux to be measured. Therefore, coils are well suited for measuring the flux inside a rope. Hence, main flux instruments can measure the longitudinal magnetic flux inside the rope directly, with great accuracy and resolution.

Figure 4 illustrates the underlying principles of the new main flux instruments. As in the previous LF/LMA return flux instruments, permanent magnets induce a magnetic DC flux in the wire rope in the longitudinal direction and magnetically saturate the rope. A concentric coil surrounds the rope. Any change of the metallic cross-sectional area *A* of the rope (caused by flaws such as corrosion, abrasion, or broken wires) causes a change of the main flux ϕM in the rope. Hence, as the rope moves, the changing main flux induces a voltage in the test coil which is proportional to the derivative of the magnetic flux ϕM. The induced voltage is integrated by the integrator circuit, whose output voltage V_I is then directly proportional to the longitudinal main flux ϕM. Since the rope is magnetically saturated, the longitudinal main flux is directly proportional to the instantaneous cross-sectional area of the rope. Hence, a change of V_I is a measure of the change in metallic cross-sectional area *A*.

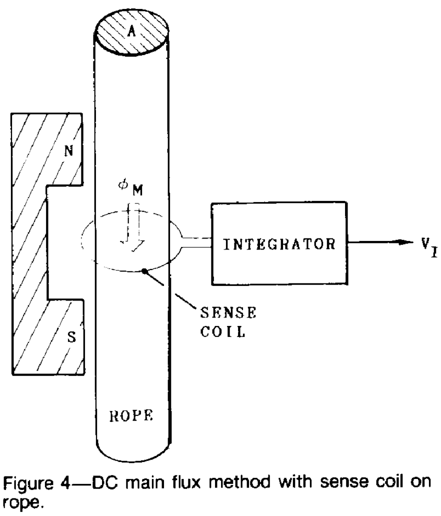

Figure 4—DC main flux method with sense coil on rope.

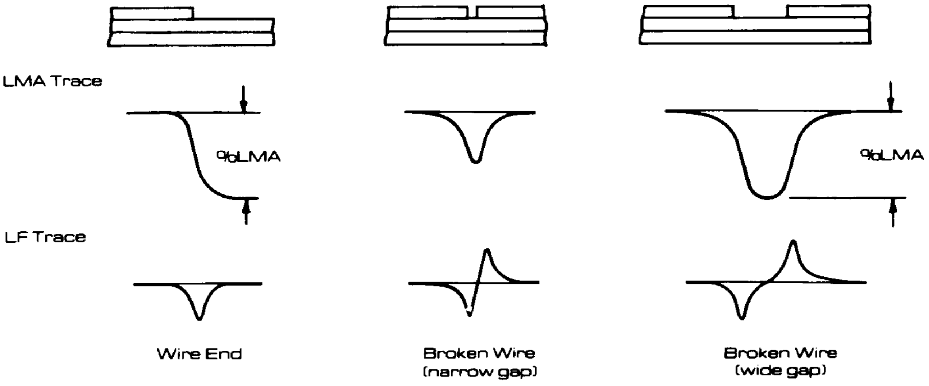

Figure 5—Catalog of standard flaws.

The approach shown in Figure 4 was recently proposed, independently, in Germany.[21] However, the coil shown in Figure 4 is not practical, because it cannot be subdivided for mounting the instrument on the rope. The new LMA main flux instruments overcome this problem by using the principles illustrated in Figure 4, together with a proprietary subdivided sense coil design and signal-conditioning circuitry.[27]

Instrument Performance

To compare and illustrate the performance of instruments, broken or missing wires are convenient to use as standard flaws because they are often present in a rope or, if no broken wires are present, because they can be simulated by attaching wires to the rope. As compared to corrosion and abrasion, broken wires have a well defined geometry and are easily reproducible. Corresponding signals, caused by standard flaws, are called standard signals. A comparison of standard signals, caused by identical flaws, gives considerable insight into the performance of different instruments.

Figure 5 shows a catalog of standard flaw signals including a symbolic representation of the corresponding standard flaws. Figure 6 shows an actual chart recording by a main flux instrument of a rope with well defined standard flaws. Using the above defect catalog, this chart recording is self-explanatory. Note the ease of test data interpretation for this particular example. Even moderately experienced personnel can usually perform a reliable chart evaluation.

The chart recordings in Figure 7 were obtained by two different instruments. The rope under test has a considerable number of broken wires which can, as mentioned above, be used as standard flaws to compare the performance of the two instruments.

Figure 7 shows the difference in performance of an LMA/LF main flux instrument and an LMA/LF return flux instrument. The main flux instrument has a quantitative resolution of 2 in. (5 cm) whereas the quantitative resolution of the return flux instrument is approximately 20 in. (51 cm). This difference is clearly discernible by comparing the two LMA traces.

The main flux instrument shows all broken wires with gap widths longer than 2 in. (5 cm) as metallic area losses of approximately 1 percent. Broken wires with gap widths less than 2 in. (5 cm) are also indicated in the LMA trace, although not with their full magnitude.

Because of its lower quantitative resolving power, the LMA trace of the return flux instrument indicates almost no LMA caused by broken wires.

At one point, the two LMA traces show an insignificant increase in metallic cross section of less than 1 percent—probably caused by a slight rope deformation.

The LF traces of both chart recordings clearly indicate numerous broken wires. The LF signal traces of most presently available instruments are approximately equivalent and easily reproducible, even for instruments of completely different design.

Note that the LMA and LF traces of the main flux instrument indicate broken wires with equal clarity. However, the LMA trace allows a much more accurate and easier loss-of-strength determination. As a rule, the LF signal is only used for an easier location of broken wires, and the LMA signal is used exclusively for data interpretation. Therefore, the LF signal for main flux instruments is redundant. In many cases, it is not necessary and not used for a reliable data interpretation.

For return flux instruments, the resolution of the LMA signal is often insufficient to estimate a rope's loss of strength. Hence, to improve the reliability and accuracy of strength estimates, both the LMA and the LF signals must be considered. Since now two signals have to be evaluated simultaneously, signal interpretation becomes complicated and subjective, if not impossible. For instance, because of its low resolution, the LMA trace of the return flux instrument in Figure 7 is not very useful for loss-of-strength evaluation. A loss-of-strength estimate therefore has to rely on the LF (qualitative) signal, which is inherently unsuitable for this type of quantitative data interpretation.

Table 1 (p 1604) compares three different commercially available main flux and return flux LMA/LF wire rope inspection instruments. Note that most data of this table are taken from the manufacturers' specifications, which are subject to change.

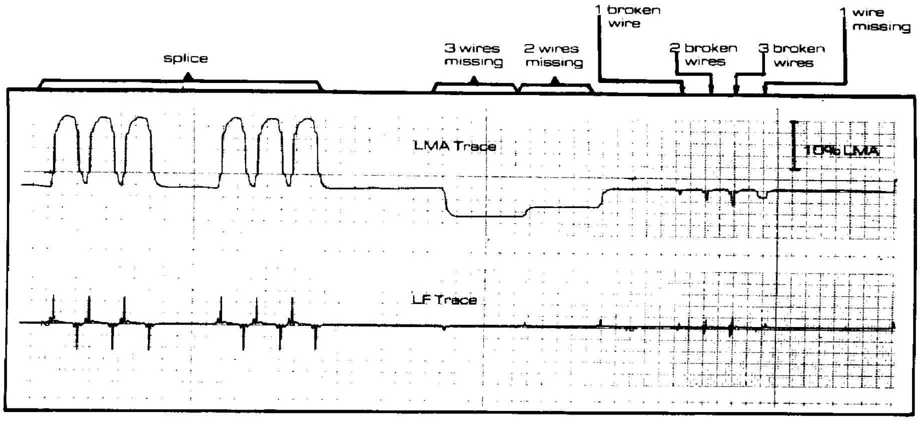

Figure 6—Chart recording of test rope with well defined standard flaws.

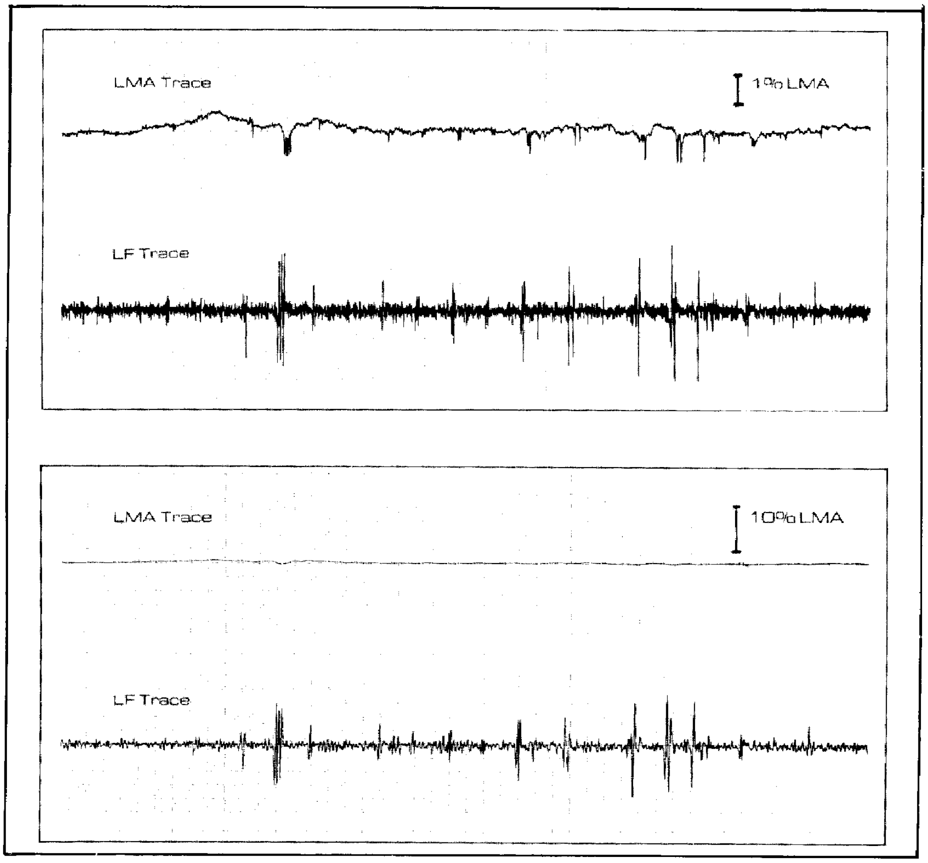

Figure 7—Performance comparison of main flux and return flux instruments.

Summary and Conclusion

Present visual methods for the inspection of wire ropes have serious deficiencies and cannot identify unsafe wire ropes which should be replaced. Furthermore, visual inspection methods are wasteful because they usually cannot identify wire ropes that have additional safe service life left.

Electromagnetic methods for nondestructive testing of wire ropes are much more reliable than purely visual methods. Nondestructive test instruments are now available which can reliably test wire ropes in service and which can remedy the shortcomings of visual wire rope inspection methods.

Two different and distinct types of nondestructive inspection methods have evolved: (1) localized fault (LF) inspection for the qualitative detection of localized flaws such as external and internal broken wires, corrosion pitting, and mechanical damage; (2) inspection for loss of metallic cross-sectional area (LMA) for the detection and quantitative evaluation of distributed flaws such as external and internal abrasion and corrosion.

Modern rope inspection instruments allow a simultaneous LMA/LF inspection. These instruments use DC magnetization of the rope, usually by permanent magnets. When the rope is magnetically saturated, the longitudinal magnetic flux in the rope is proportional to the rope's metallic cross-sectional area. Therefore, any LMA can be determined by measuring the longitudinal magnetic flux in the rope.

Two different classes of LMA/LF instruments are presently available: main flux and return flux instruments. Main flux instruments measure the flux in the rope directly, which allows a very accurate cross-sectional area determination. Return flux instruments obtain an estimate of the longitudinal flux in the rope by measuring some flux density outside the rope. An estimate of the longitudinal rope flux is then derived from this external flux density measurement.

While all modern LMA/LF instruments offer greatly improved testing reliability as compared to the previous state of the art, main flux instruments have superior resolving power, which makes data interpretation easy and very reliable.

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TABLE 1 Instrument Comparison

	LMA-250 System[a]	System A[b]	System B[b]
Instrument Type	LMA/LF main flux	LMA/LF return flux	LMA/LF return flux
Magnetization	rare earth (samarium cobalt) permanent magnets	rare earth (samarium cobalt) permanent magnets	ferrite permanent magnets
Sensors	coils	Hall generators	flux gate sensors (coils)
Quantitative Resolution[c]	2 in.	20 in.	20 in.
Electrical Power	battery or AC line (selectable)	battery or AC line (selectable)	AC line
Rope Measurement			
Rope Diameter[c]	0.38–2.50 in.	0.38–2.50 in.	0.38–2.50 in.
Rope Speed[d]	0–600 ft/min	0–600 ft/min	0–600 ft/min
Weight[e]			
Sensor Head	60 lb	105 lb	98 lb
Console Including Strip Chart Recorder	39 lb (includes batteries)	80 lb (includes batteries)	45 lb (batteries not available)
Accessories	footage counter and tape recorder	footage counter and tape recorder	footage counter

[a] NDT Technologies, Inc.

[b] Selected as current examples of the technology.

[c] 1.00 in. = 2.54 cm.

[d] 1.0 ft = 0.3 m.

[e] 1.00 lb = 0.45 kg.

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APPENDIX A

The following is a summary of those sections of the *US Code of Federal Regulations 30 (Mineral Resources)* dealing with wire rope safety.

Initial Measurement

After initial rope stretch but before visible wear occurs, the rope diameter of newly installed wire ropes shall be measured at least once in every third interval of active length, and the measurements averaged to establish a baseline for subsequent measurements. A record of the measurements and the date shall be made by the person taking the measurements. This record shall be retained until the rope is retired from service.

Examinations

(a) At least once every 14 calendar days, each wire rope in service shall be visually examined along its entire active length for visible structural damage, corrosion, and improper lubrication or dressing. In addition, visual examination for wear and broken wires shall be made at stress points, including the area near attachments, where the rope rests on sheaves, where the rope leaves the drum, at drum crossovers, and at change-of-layer regions. When any visible condition that results in a reduction of rope strength is present, the affected portion of the rope shall be examined on a daily basis.

(b) Before any person is hoisted with a newly installed wire rope or any wire rope that has not been examined in the previous 14 calendar days, the wire rope shall be examined in accordance with paragraph (a) of this standard.

(c) At least once every six months, nondestructive tests shall be conducted of the active length of the rope, or rope diameter measurements shall be made (1) wherever wear is evident, (2) where the hoist rope rests on sheaves at regular stopping points, (3) where the hoist rope leaves the drum at regular stopping points, and (4) at drum crossover and change-of-layer regions.

(d) At the completion of each examination required by paragraph (a) of this standard, the person making the examination shall certify, by signature and date, that the examination has been made. If any condition listed in paragraph (a) of this standard is present, the person conducting the examination shall make a record of the condition and the date. Certifications and records of examinations shall be retained for one year.

(e) The person making the measurements or nondestructive tests as required by paragraph (c) of this standard shall record the measurements or test results and the date. This record shall be retained until the rope is retired from service.

Retirement criteria

Unless damage or deterioration is removed by cutoff, wire rope shall be removed from service when any of the following conditions occurs: (a) The number of broken wires within a rope lay length, excluding filler wires, exceeds either 5 percent of the total number of wires or 15 percent of the total number of wires within any strand; (b) on a regular lay rope, there are more than one broken wire in the valley between strands in one rope lay length; (c) a loss occurs of more than one-third of the original diameter of the outer wire; (d) rope deterioration from corrosion; (e) the rope structure is distorted; (f) there is heat damage from any source; (g) diameter reduction due to wear exceeds 6 percent of the baseline diameter measurement; or (h) loss of more than 10 percent of rope strength occurs, as determined by nondestructive testing. Ω